LLNL-CONF-426094

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J. Lundquist, L. Glascoe, J. Obrecht

March 18, 2010

The Fifth International Symposium on Computational Wind Engineering
Chapel Hill, NC, United States
May 21, 2010 through May 23, 2010

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J.K. Lundquist[a], L. Glascoe [b], J. Obrecht [c]

[a]*University of Colorado at Boulder, Boulder, CO, United States, julie.lundquist@colorado.edu*
[b]*Institutional Lawrence Livermore National Laboratory, Livermore, CA, United States, glascoe1@llnl.gov*
[c]*Siemens Energy, Inc., Boulder, CO, United States, john.obrecht@siemens.com*

ABSTRACT: Accurate short-term forecasts of wind resources are required for efficient wind farm operation and ultimately for the integration of large amounts of wind-generated power into electrical grids. Siemens Energy Inc. and Lawrence Livermore National Laboratory, with the University of Colorado at Boulder, are collaborating on the design of an operational forecasting system for large wind farms. The basis of the system is the numerical weather prediction tool, the Weather Research and Forecasting (WRF) model; large-eddy simulations and data assimilation approaches are used to refine and tailor the forecasting system. Representation of the atmospheric boundary layer is modified, based on high-resolution large-eddy simulations of the atmospheric boundary. These large-eddy simulations incorporate wake effects from upwind turbines on downwind turbines as well as represent complex atmospheric variability due to complex terrain and surface features as well as atmospheric stability. Real-time hub-height wind speed and other meteorological data streams from existing wind farms are incorporated into the modeling system to enable uncertainty quantification through probabilistic forecasts. A companion investigation has identified optimal boundary-layer physics options for low-level forecasts in complex terrain, toward employing decadal WRF simulations to anticipate large-scale changes in wind resource availability due to global climate change.

1 INTRODUCTION

Accurate short-term forecasts of wind resources are required for efficient wind farm operation and for the integration of large amounts of wind-generated power into electrical grids. Especially in regions with significant penalties for unfulfilled power commitments or for incorrect forecasts, robust and accurate forecasting tools are required to ensure the success of wind farms and the penetration of significant amounts of renewably-produced electricity into power grids.

The need for accurate forecasting tools is present at several scales. In the near-real time forecast period, from a few minutes to 1-2 hours ahead of time, forecasts can provide alerts on severe weather events that could impact grid reliability. In the 0-6 hour ahead forecast period, accurate forecasts enable anticipation and management of changes in wind that affect output from a wind farm. Short-term reserve capacity to supplement wind power generation may also be scheduled with information from these short-term forecasts. Finally, forecasts in the one-to-several-days-ahead period may be used to optimize maintenance schedules around weather patterns that determine production of electricity from the wind as well as enable skillful energy trading.

1.1 *Modeling approach*

The heart of this atmospheric modeling system is the Weather Research and Forecasting (WRF) model, an open-source numerical weather prediction model supported by a large community of users. The WRF model can be run at different mesh resolutions and domain sizes, from mesoscale simulations to large-eddy simulations, enabling the representation of a wide scale of physical processes, from the wakes resulting from individual turbines to synoptic weather events to climate-scale weather oscillations.

The WRF modeling system is coupled with the Data Assimilation Research Testbed (DART) system to incorporate data streams from operating wind farms in ensemble forecasting approaches. Not only do these data streams allow refinement of individual forecasts, but they also provide the basis for an ensemble modeling approach that enables quantification of the uncertainty of the forecast.

1.2 *Detailed discussion of modeling developments*

Several companion papers on this project are presented at the Computational Wind Engineering 2010 meeting to present aspects of this work in more detail. Herein, we highlight approaches to simulation and representation of turbine wakes (Singer et al., 2010), ensemble-based data assimilation (Delle Monache et al., 2010), and determination of optimal WRF boundary-layer physics routines (Chin et al., 2010b).

2 WAKE EFFECTS

As discussed in a companion paper (Singer et al., 2010), wind turbine wakes significantly impact flow dynamics both within wind parks and downstream. For the purposes of this project, the most significant region of low wind speed immediately downwind of a turbine reduces the available wind speed for downwind turbines, resulting in power deficits on the order of 40% for downwind turbines (Barthelmie et al., 2007). To accurately forecast available total power at a wind farm, therefore, wind turbine wakes must be represented in forecasting models.

Additionally, regions of low-speed flow immediately behind the turbines can elevate the level of turbulence for considerable distances downstream. These turbulent stresses may increase turbine loading and accelerate component fatigue, thereby decreasing machine reliability, lifespan, and operating time, while increasing maintenance costs.

2.1 *Choice of modeling platform*

Large wind parks support a multitude of flow phenomena that occur over a large range of spatial scales. In a typical offshore park, for example, individual turbines may be separated by 500-1000 m, and the entire park may occupy 20-30 km^2. Hence, mesoscale modeling, which typically resolves flow features down to approximately 5 km, is an appropriate tool for understanding the impact of wakes on flow throughout the entire park and the surrounding area. In contrast, the near wakes produced by the turbines, whose typical rotor diameters are around 100 m, generally extend 1-3 rotor diameters downstream of the turbine. Therefore, higher resolution models, such as large-eddy simulations (LES), are required to capture the relatively small-scale features of the near wake. This large disparity in length scales at which flow features occur presents numerous modeling challenges that require flexible numerical algorithms and computational models.

The Weather Research and Forecasting (WRF) atmospheric simulation model is an ideal testbed for implementing and assessing different wake models and parameterizations.The code is open-source and is supported by a large community of users. This flexibility facilitates the formulation and implementation of wake models for use within the WRF code. In addition, the

WRF model can be run at different mesh resolutions and domain sizes, from mesoscale simulations to LES, which addresses the broad range of length scales that must be considered in wake modeling. A variety of physics options (e.g., boundary layer schemes, turbulence models, radiation and surface parameterizations) as well as data assimilation techniques are readily available in the WRF model, which enables the validation of the wake models against observations collected in a complex atmosphere. Many such physical processes may be important to developing a thorough understanding of the formation, transport, and impact of turbine wakes, especially across the broad range of variability in weather encountered by wind projects sited in disparate locations with different climatologies. The WRF model provides a rich set of functionality that, when combined with wake models, is capable of advancing our ability to characterize and predict wakes from large wind projects, as well as their effects on neighboring physical processes and activities.

2.2 *Actuator disk model in WRF*

As presented in detail in the companion paper (Singer et al., 2010), an actuator disk model is implemented into the WRF model. An example simulation of a four-by-four array of wind turbines in neutral flow appears in Figure 1. Simulations of the wake effects in various atmospheric flow regimes (convective, neutral, stable) will provide insight into the effects of turbine wakes in large wind projects. Large-eddy simulations with the actuator disk model are being used to develop a wake effect parameterization for use in mesoscale applications.

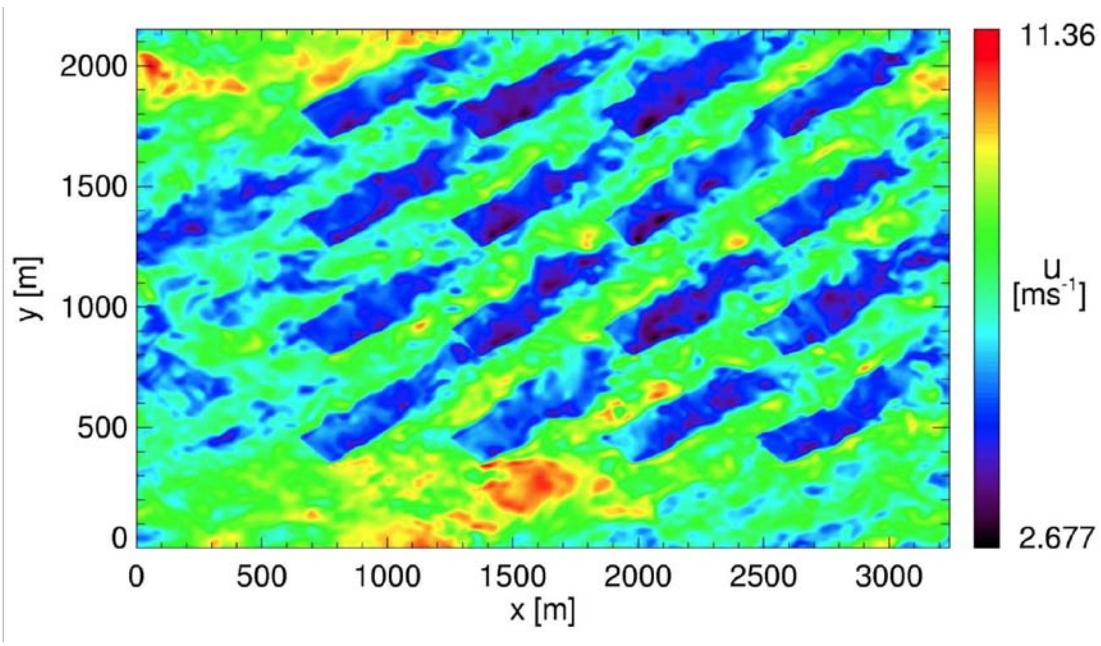

Figure 1. Instantaneous view of the zonal velocity component at 100m above the surface. The low-wind-speed wake behind each disk in the 4x4 array of actuator disks appears in blue. From Singer et al, 2010.

3 DATA ASSIMILATION

As discussed in a companion paper (Delle Monache et al., 2010), the assimilation of numerous data streams into a forecast model enables a probabilistic approach to wind energy forecasting. The methodology proposed here is based on the ensemble Kalman Filter (EnKF - Evensen 1994). The Kalman filter integrates a predictive model (e.g., a weather forecasting model) of a dynamical system (e.g., the atmosphere), known control inputs to that system, and measurements (from surface sensors, upper-air radiosonde, etc.) to estimate the system state. The result is a distribution of forecasts, rather than a single deterministic forecast, and therefore provides a probabilistic estimate of forecast uncertainty. This distribution is conditioned on the observations.

3.1 *Choice of modeling system*

The EnKF algorithms proposed here are included in the Data Assimilation Research Testbed (DART) system (Anderson et al. 2009). DART is an open-source ensemble data assimilation system that includes state-of-the-science algorithms for data assimilation and weather prediction (http://www.image.ucar.edu/DAReS/DART/). The numerical weather prediction model we will employ within the DART system is the Weather Research and Forecasting (WRF) Advanced Research (ARW) model (Skamarock et al. 2005).

One of the advantages of a community model such as WRF is the possibility of choosing among several parameterizations to model physical phenomena (e.g., boundary layer, surface layer, cloud microphysics, etc.). This flexibility provides the opportunity to characterize modeling errors by running each ensemble member with a different physics configuration (in addition to the perturbed initial conditions provided by DART). Tests based on historical data will determine if DART should be run with the addition of adaptive covariance inflation or with a multi-physics ensemble, or a mixture of both approaches.

4 SENSITIVITY OF LOW-LEVEL WINDS TO WRF MODEL PHYSICS AND GRID RESOLUTION

A companion paper (Chin et al., 2010b) summarizes recent findings indicating optimal WRF boundary-layer physics parameterizations for two different inland wind farms in clear-sky conditions. To prepare for multi-decadal regional climate model simulations with WRF to delineate possible climate change impacts on wind resources, several short-range simulations are validated against observations.

4.1 *Horizontal grid resolution*

The impact of terrain resolution on wind forecast is tested with simulations of five resolutions: 36, 12, 4, 1.333, and 0.444 km. For these simulations, WRF is configured with 41 vertical levels with a constant grid spacing of 20 meters below the lowest 200 meters, with gradual stretching aloft. For the case explored in California, with more complex terrain, the utility of high horizontal resolution is clear: the 1.33km horizontal resolution simulations agree well with observations. For the Texas cases, the impact of grid resolution is not as clear, and Chin et al. 2010b conclude that the terrain gradients in Texas do not exert as strong of an influence on boundary-layer dynamics as do the terrain gradients in California.

4.2 *Boundary-layer physics schemes*

For the exploration of boundary-layer physics, four options of PBL physics (YSU, MYJ, MYNN, and ACM2), three options of surface physics (Monin- Obukhov; M-O, MYNN, and Pleim-Xu), and two options of soil physics (RUC and Pleim-Xu) are tested. Due to the constraint of pair usage of some model physics, only seven combinations are available in this study. The rest of model physics set-up such as microphysics (two-moment Morrison scheme), cumulus (Grell-Devenyi), and radiation transfer (CAM) is based on prior experience in regional climate simulations (Chin et al., 2010a).

In the California simulations, two combinations of optimal combination of physics parameterizations emerged. These configurations exhibited similarly small root-mean- square-error (RMSE): MYNN PBL + Monin-Obukhov surface layer + RUC soil physics and ACM2 PBL + Monin-Obukhov surface layer + RUC soil physics. However, in the Texas simulations, no optimal configuration emerged for the selected case studies. One configuration did exhibit a higher likelihood for minimum RMSE at all measurement stations over all events; that configuration consists of the MYJ PBL + Monin-Obukhov surface layer + RUC soil physics. This configuration is used for the ongoing decadal regional climate studies to assess the impact of climate change on future wind resources in the continental United States.

5 SUMMARY

Accurate short-term forecasts of wind resources are required for efficient wind farm operation and ultimately for the integration of large amounts of wind-generated power into electrical grids. Siemens Energy Inc., and Lawrence Livermore National Laboratory, with the University of Colorado at Boulder, are collaborating on the design of an operational forecasting system for large wind farms. The basis of the system is the numerical weather prediction tool, the Weather Research and Forecasting (WRF) model.

The complete development of a forecasting tool requires the integration of several advances in atmospheric modeling. Three of these advances are described herein. First, the implementation and validation of a turbine wake model into a large-eddy simulation formulation of WRF provides grounds for the development of a mesoscale wake parameterization that responds to atmospheric variability. Second, the integration of operational wind farm data streams via an Ensemble Kalman Filter enables both refinement of forecasts based on observations as well as uncertainty quantification via probabilistic forecasts. Finally, an optimal configuration of boundary-layer physics schemes, based on a limited set of observations at operating wind farms, has been defined. This configuration is in use for the quantification of climate change impacts on wind resources.

Other components of this forecasting project are in development. The ultimate goal of this project, accurate and timely forecasts of power availability, will enable turbine owners and operators to generate optimal bids on wind turbine production and in turn maximize both financial benefit and support for the increased penetration of renewably-generated electricity into power grids.

6 ACKNOWLEDGEMENTS

This work was supported by Siemens Energy, Inc. LLNL is operated by Lawrence Livermore National Security, LLC, for the DOE, National Nuclear Security Administration under Contract DE-AC52-07NA27344. The authors gratefully acknowledge the efforts of all the Siemens-LLNL-UCB-NCAR team, particularly the co-authors of each of the companion papers referred to herein.

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